

BIOTECHNOLOGY OPENS NEW ROUTES TO HIGH-PERFORMANCE MATERIALS FOR IMPROVED PHOTOVOLTAICS, BATTERIES, UNCOOLED IR DETECTORS, FERROELECTRICS AND OPTICAL APPLICATIONS

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ABSTRACT

Biological systems fabricate multifunctional, high-performance materials at low temperatures and near-neutral pH with a precision of three-dimensional nanostructural control that exceeds the capabilities of present human engineering. Using the tools of biotechnology and genetic engineering, we discovered the unanticipated mechanism of simultaneous catalysis and templating governing the nanofabrication of silica in a biological system. We then translated this mechanism to develop a new biologically inspired, low-temperature, low-cost route for the synthesis of silica and a wide range of silicones, organic polymers and nanostructured metal oxide, -hydroxide and -phosphate semiconductor thin films without the use of organic templates. This new synthesis method is generic, yielding more than 30 different inorganic thin films and nanostructured, bimetallic perovskite ferroelectrics. Because kinetic control is achieved at low temperature, thus circumventing the thermodynamic default, many of the inorganic materials made by this process exhibit morphologies and electronic properties not observable in the corresponding products made by conventional high temperature processes. The electronic properties of some of these novel materials suggest strong advantages for high-efficiency photovoltaics, lightweight high power-density 3-D batteries, improved battery safety, uncooled IR detectors and other energy and information storage applications. Because no organics are used, the resulting products exhibit very high purity, making the process fully integrable with MOCVD and other conventional manufacturing methods. Because synthesis occurs from solution, adaptation to roll-to-roll and other high throughput methods may be possible. Transitioning of these developments to Army applications is now beginning. Related efforts now in progress are focused on revolutionary, bio-inspired approaches to optical materials.

1. OVERVIEW AND ARMY SIGNIFICANCE

We discovered the molecular mechanism governing the biological nanofabrication of silica in a group of marine sponges (Shimizu, et al., 1998; Cha et al., 1999; Morse, 1999, 2001; Zhou et al., 1999; Weaver et al., 1999;

Aizenberg et al., 2005), and translated this mechanism to a radically new generic method for the low-temperature synthesis of a wide-range of nanostructured semiconductor thin films with properties uniquely advantageous for more efficient energy generation and storage (Schwenzer et al., 2005; Kisailus et al., 2006; Brutchey and Morse, 2006). We have demonstrated that because this method operates at low temperature by kinetically controlled catalysis it yields materials with compositions and properties often not attainable by conventional high-temperature synthesis. The method is widely generic, thus far allowing us to produce more than 30 different nanostructured thin film metal oxides, hydroxides and phosphates - many in forms and with properties not achievable before. We have demonstrated *in situ* conversion of the as-formed materials to the corresponding nitrides, sulfides and phosphides, further extending the range of materials important for energy applications that are accessible by this new method. The kinetic control delivered by this method yields good crystallinity, long minority carrier lifetimes, high dopant densities and high surface areas *all of which are advantageous for more efficient solar energy and lightweight, high power-density 3-d batteries*. Because no organics or biochemicals are used, the method produces very high purity materials that are fully integrable with MOCVD and CMOS fabrication. We have shown the method capable of producing both substrate-supported and free-standing thin films. Because the method operates at low-temperature and near-neutral pH, we have found it uniquely advantageous for growing TiO_2 and ZnO electrode layers on the temperature-sensitive layers of organic polymer photovoltaics being explored by Army Laboratories at ARL and CERDEC for lightweight, flexible, soldier-carried solar energy cells. Because the synthesis method is solution-based, it is potentially adaptable to roll-to-roll and other high-throughput manufacturing methods.

We also found that the new synthesis method we developed can be used with advantage to make highly crystalline bimetallic oxide perovskites, such as $BaTiO_3$, a valuable ferroelectric, piezoelectric and thermoelectric material with useful applications in energy transduction, magnetic information storage, ambient temperature (uncooled) IR detection, and improvements in safety of lithium ion batteries (Brutchey and Morse, 2006). By

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combining the advantages of unique bimetallic precursor molecules with the gentle, low-temperature and vectorially controlled catalysis method we developed, we show that we are able to make novel bimetallic perovskites with never-before achieved control over the stoichiometry and atomic-scale geometry of the two metal centers, without the complications of phase-segregation and degradation of properties typical of high-temperature methods.

2. TRANSLATION FROM BIOLOGY TO SEMICONDUCTOR SYNTHESIS

With a precision of nanostructural control that exceeds present human capabilities, biological systems fabricate 3-D multifunctional high-performance silicon-based materials at low temperatures and near-neutral pH. The fundamental molecular biology of silica production in sponges and diatoms is now being elucidated, and aspects of these processes are being harnessed for industrial and technological processes. Working with the silica needles produced by marine sponges, our laboratory discovered that proteins we named "silicateins" catalyze and structurally direct the polymerization of silica, organically substituted silsesquioxanes (silicones) and organometallic silsesquioxanes from the corresponding silicon alkoxides at neutral pH and low temperature (Shimizu, et al., 1998; Cha et al., 1999; Morse, 1999, 2001; Zhou et al., 1999; Weaver et al., 1999). The silicateins are true enzymes, closely related to a well-known family of hydrolases (Shimizu et al., 1998). Interestingly, we were able to show that these enzymes also catalyze and structurally direct the synthesis of a number of metal oxide semiconductors from the corresponding molecular precursors Sumerel et al., 2003; Kisailus et al., 2005a; Brutney et al., 2006). These are the first reported examples of enzyme-catalyzed, nanostructure-directed synthesis of semiconductors. Interaction with the template-like protein surface stabilizes polymorphs of these materials (e.g., the anatase form of titanium dioxide and the spinel polymorph of gallium oxide) otherwise not formed at low temperatures. In some cases, interaction between the condensing metallo-oxane and the protein results in preferential alignment of the resulting nanocrystallites, suggesting a pseudo-epitaxial relationship between the mineral crystallite and specific functional groups on the templating protein surface (Kisailus et al., 2005a).

Site-directed mutagenesis of the cloned recombinant DNAs coding for the silicateins confirmed the mechanism of catalysis (Zhou et al., 1999), and has been used to increase the rate of catalysis as well. These studies enabled the synthesis of self-assembling "biomimetics" - peptides, polymers, and self-assembled monolayers on nanoparticles and on planar surfaces - that incorporate the functionalities identified as essential for catalysis, yielding new structure-directing catalysts of polymerization (Cha et al., 2000;

Kisailus et al., 2005b, 2006b; Roth et al., 2005). But to achieve the high purity of semiconductors required for most applications, it proved necessary to further translate the advantages of the biomolecular mechanism of synthesis to a method that employs no organic or biochemical molecules, and thus removes that source of contamination from the synthesis pathway.

We now report the successful translation of the underlying principles governing this structure-directing synthesis to a new method capable of the low-temperature nanofabrication of metal oxide semiconductors without the use of any organic or biochemical templates (Schwenzer et al., 2005; Kisailus et al., 2006b; Brutney and Morse, 2006). We discovered that the fundamental enabling principles responsible for the unique low-temperature biological nanofabrication of silica and semiconductor crystalline materials were two-fold: (1) slow enzymatic catalysis of synthesis from molecular precursors made it possible for kinetic control of the synthesis reactions to circumvent the thermodynamic default, producing in some cases crystal polymorphs of the semiconductors, at low temperature (16 °C), that otherwise could only be made only at very elevated temperatures (>400 °C); and (2) this control of polymorph and crystal form was the result of templating imposed by interactions between the growing nanocrystallites and the enzyme (protein) surface - and effect that could be approximated by imposing an alternative means for anisotropically (i.e., vectorially) structuring the crystal-growth environment. As a first proof of principle that we could translate these advantages of the biological synthesis mechanism to a method utilizing no organics, we demonstrated the low-temperature synthesis of a unique, strongly photoconductive cobalt hydroxide-based material, never before achievable through conventional or high-temperature methods, with attractive properties of high dopant density, high carrier density, exceptionally long minority carrier density and strong absorption in the visible, appropriate for photovoltaic applications (Schwenzer et al., 2005).

3. KINETICALLY AND VECTORIALLY CONTROLLED LOW-TEMPERATURE CATALYSIS OF SEMICONDUCTOR NANOFABRICATION

The generic method we developed uses vapor diffusion of ammonia or other catalysts through a gas-liquid interface into a solution of molecular precursor to provide the vectorial control of catalysis, at low-temperature, of synthesis from molecular precursors that require hydrolysis (Schwenzer et al., 2005). The approach proves readily useful with a wide range of catalysts including acids, bases and water (Brutney and Morse, 2006). The result is a novel, highly generic low-temperature and

environmentally benign method for the nanofabrication of a wide range of more than 30 different metal oxide, metal hydroxide and metal phosphate semiconductors, in unique and potentially useful crystal morphologies - some of which could never have been made before - with significantly enhanced electronic performance (Schwenzer et al., 2005; Brutney and Morse, 2006). The method relies on the integrated tuning of molecular precursors and vectorially controlled catalysis, utilizing only chemical physics and highly purifiable inorganic components, *with no biochemicals, biologicals or organic materials*. In situ conversion to the nitrides, sulfides and phosphides has been shown to extend the range of materials that can be made by this method - many with properties useful for photovoltaic or battery applications. The use of the molecular precursor and its vectorially controlled catalytic hydrolysis provide coordinate kinetic and directional control of semiconductor growth that is not available using conventional high-temperature approaches.

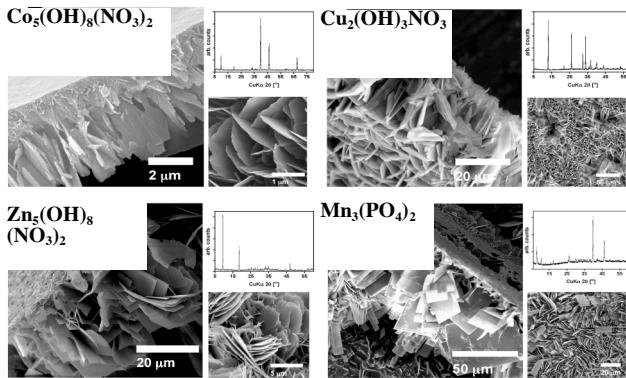


Fig. 1. Representative examples of the nanostructured semiconductor thin films synthesized by the new method described above. Examples shown are cobalt hydroxide, copper hydroxide, zinc hydroxide and manganese phosphate. Insets show the X-ray diffraction patterns of the materials, confirming excellent crystallinity.

By tuning the directionally controlled delivery of the catalyst and the structure of a molecular cobalt-based precursor, for example, the low-temperature solution route described above produces a high surface area array of large single crystal p-type semiconductor plates of $\text{Co}(\text{OH})_2$ (ca. 20 nm thick) projecting orthogonally from, and all intimately connected to, a flat and continuous conductive backplane of the same material (Schwenzer et al., 2005). XRD, electronic diffraction, XPS and other physical characterization reveal that the plates are highly doped, high surface area single-crystal $\text{Co}(\text{OH})_2$ in the hydrotalcite crystal structure (see figures below). The material is highly doped with anions (dopant density = $3.5 \times 10^{20} \text{ m}^{-3}$) intercalated between the crystal plates, facilitating conductivity. X-ray diffraction and electron diffraction results indicate the same structure, demonstrating homogeneity from nanoscale to macroscale dimensions. Electrical measurements show that the

material is a p-type semiconductor with good conductance in the semiconductor regime, and that it acts as an efficient photoconductive transducer with high carrier density and long minority carrier half-life. The material exhibits strong absorption in the visible, with a band-gap of 1.9 eV. The work function also has been characterized.

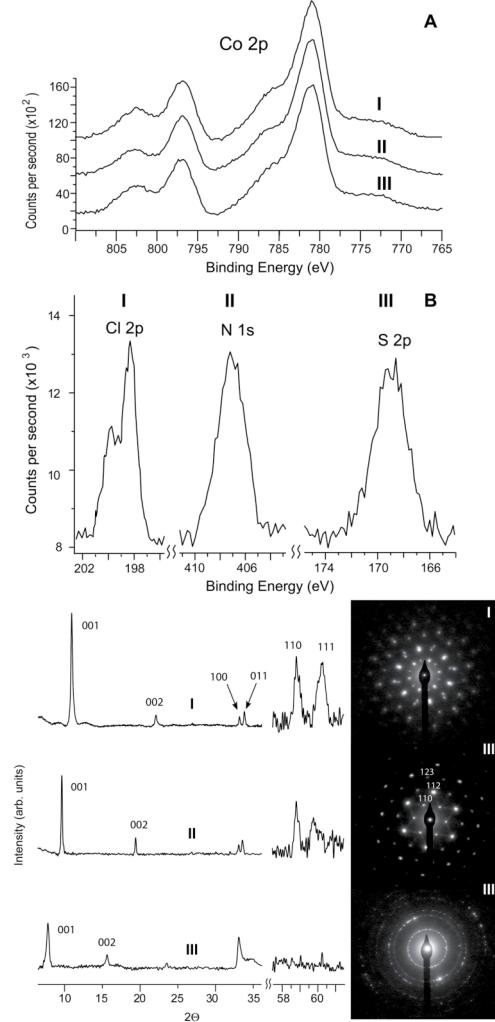


Fig. 2. Figures above: I = chloride-doped; II = nitrate-doped; III = sulfate-doped cobalt hydroxide materials made by the bio-inspired, low-temperature nanostructured catalytic process described above. (See Fig. 1, upper-left quadrant, for illustration of II.)

(Top two panels): High resolution XPS spectra of (A) Co 2p region for I, II, and III and (B) Cl 2p, N 1s and S 2p regions for I, II, and III respectively.

(Lower three panels and diffraction patterns): Powder XRD and electron diffraction patterns for I, II, and III showing peaks indexing to the brucite structure with $a_{I,II,III} = 3.13$; $c_I = 8.12$; $c_{II} = 9.19$; and $c_{III} = 11.26$.

Electrical measurements (using an interdigitated electrode array) confirm that material exhibits excellent ohmic conductance (with very low dark sheet dark sheet resistance = $5.9 \times 10^{-4} \Omega \text{ cm}$), and that it acts as an efficient

photoconductive and photovoltaic transducer with a band-gap at 1.9 eV, a high carrier density and long minority carrier half-life. This long minority carrier half-life is a reflection of the high crystallinity and high purity of the material (achieved because our synthesis method, although bio-inspired, uses no organics or biochemicals of any kind). While measured for photoconductive behavior, the long carrier (electron) path-length also indicates an excellent property for high efficiency performance in electrical batteries.

In a project recently begun in collaboration with the U.S. Army's CERDEC and a commercial battery manufacturer, we are exploring the utility of nanostructured cobalt- and iron-based materials made by the bio-inspired low-temperature method described above for potential advantages in 3-dimensional high power-density batteries. Use of the barium titanate nanoparticles made by this method also are being investigated for their potential to quench runaway reactions at battery electrodes by virtue of the material's unique positive thermal coefficient of resistance, to thereby increase the safety of lithium ion batteries.

4. CONCLUSIONS AND PROSPECTS

A new generic, low-cost, low-temperature, biologically inspired method for the synthesis of nanostructured thin-films and nanoparticles of a wide range of metal oxide, hydroxide and phosphate semiconductors and bimetallic perovskites was developed with support from the Army. Advantages of previously unprecedented control over composition and structure offered by this method enables some of these materials to be produced in forms never before achievable, and with electronic properties not previously available. Advantages of performance, purity of the resulting materials (made with no organic contaminants), the simple solution-based synthesis method, integrability with conventional manufacturing and advantages of cost suggest a wide range of applications including higher efficiency photovoltaics, high-power density batteries, improved battery safety, IR detectors, flexible displays, ferroelectric random-access memory (FeRAM) information storage and other optoelectronic applications. Several of these now are under active investigation with the aim of accelerating transition to the Army, in collaborations supported by ARO ARL, CERDEC and DARPA.

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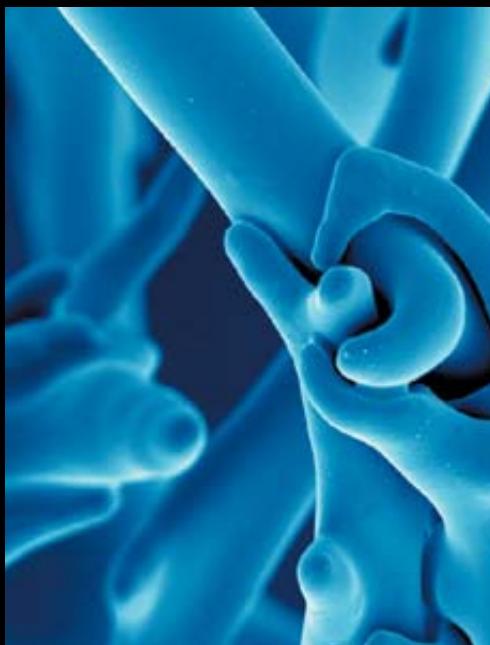
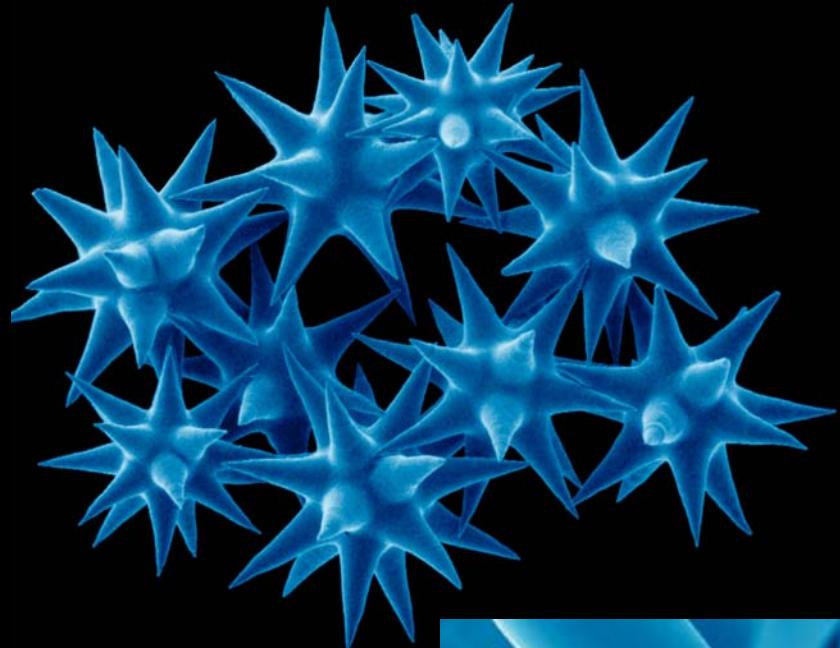
Biotechnology Opens New Routes to High-Performance Materials

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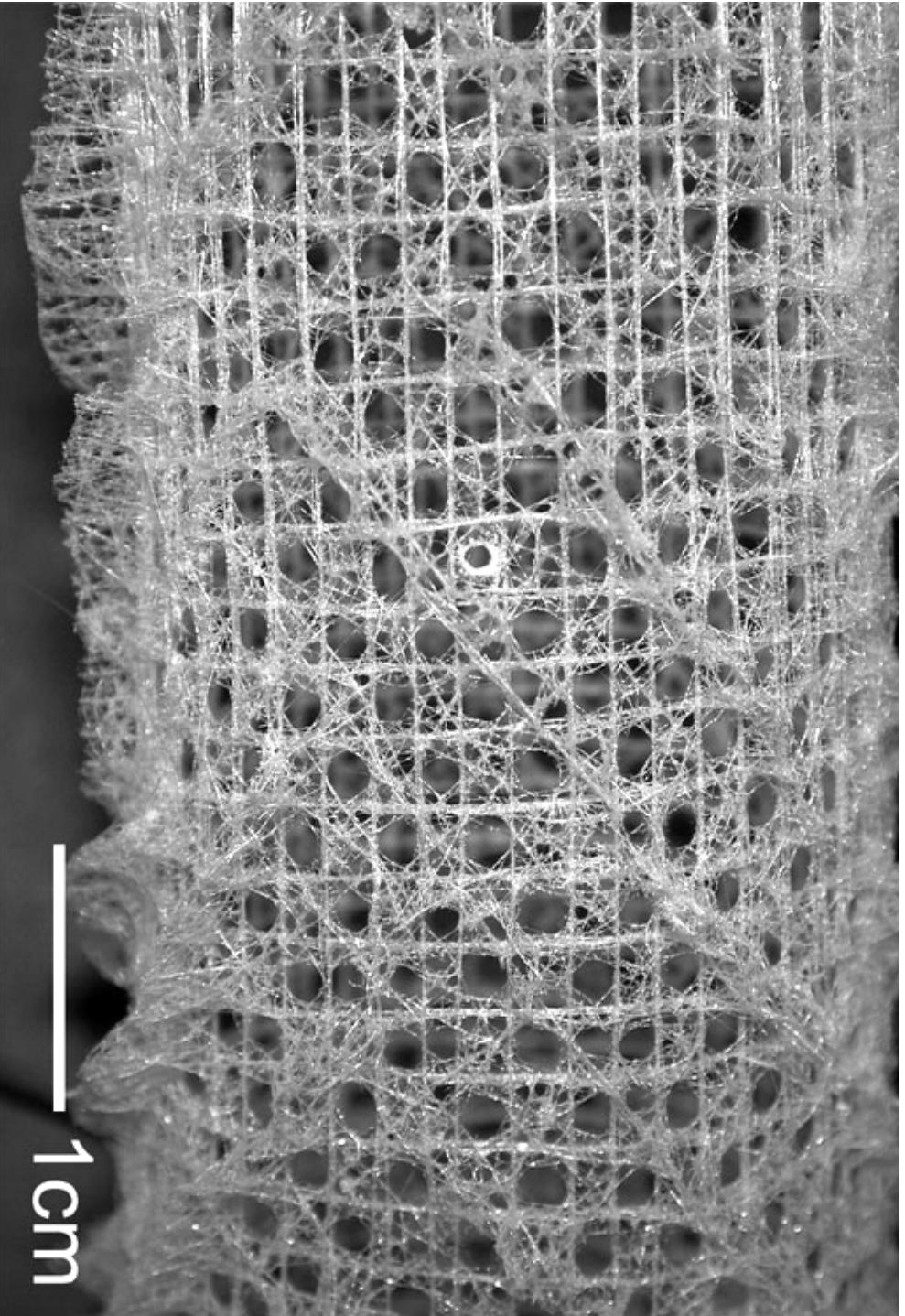
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Santa Barbara



Remarkable Structures of Bio-silica in Sponges



1 cm



- Biotechnology revealed previously unsuspected mechanism of low-temp. catalysis & templating

- Developed “Silicon Biotechnology,” leading to \$50 M spin-off to Dow Corning and Genencor

- Translated to generic low-T catalytic synthesis of ultrapure semiconductor nanostructured thin films and nanopartiparticles

- Unique advantages for High Power-Density, Safe Batteries and Solar Energy applications



**GENETIC GEN
ENGINEERING NEWS**

Silicon Biotechnology

Vol. 21, No. 10, November 13, 2003

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Genencor and Dow Corning Team Up to Make New Products

Carol Potera

Looking for unique opportunities in megatrends, such as biotechnology and materials science, would appear to be a good business strategy in today's high-tech world. The leaders of Genencor International, Inc. (Palo Alto, CA) and Dow Corning Corp. (Midland, MI) took that approach and formed a strategic alliance to create a new technology platform, called Silicon Biotechnology™.

This merger of silicon chemistry and biotechnology represents "Genencor's theme of pushing the boundaries of biotechnology," says

Thomas Mitchell, president and CEO of Genencor. In fact, the concept of Silicon Biotechnology is so new that he knows of no other company designing products that intersect both disciplines. "That's what makes it so exciting," adds Mitchell, who envisions revolutionary new products that will benefit

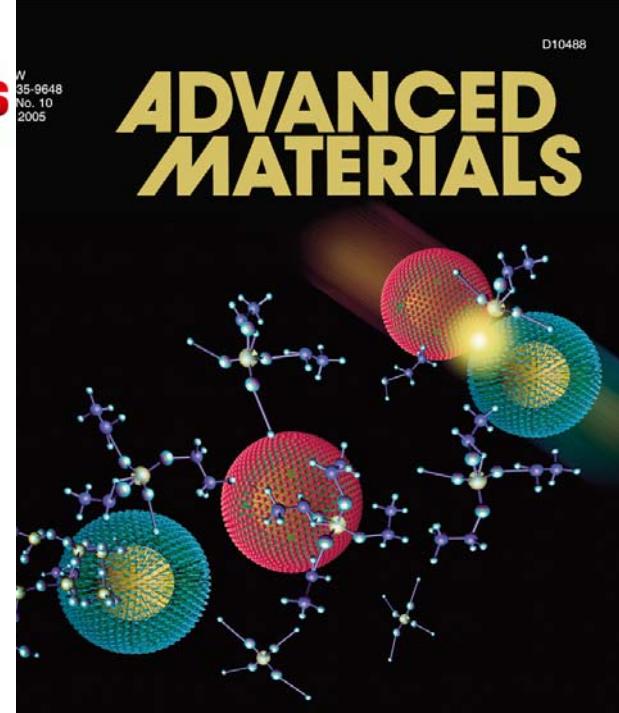
both industrial and health-care-based customers.

Dow Corning is the world's largest manufacturer of silicon materials, which are found in cosmetics, personal care items, detergents, computer chips, plastics, and textiles.

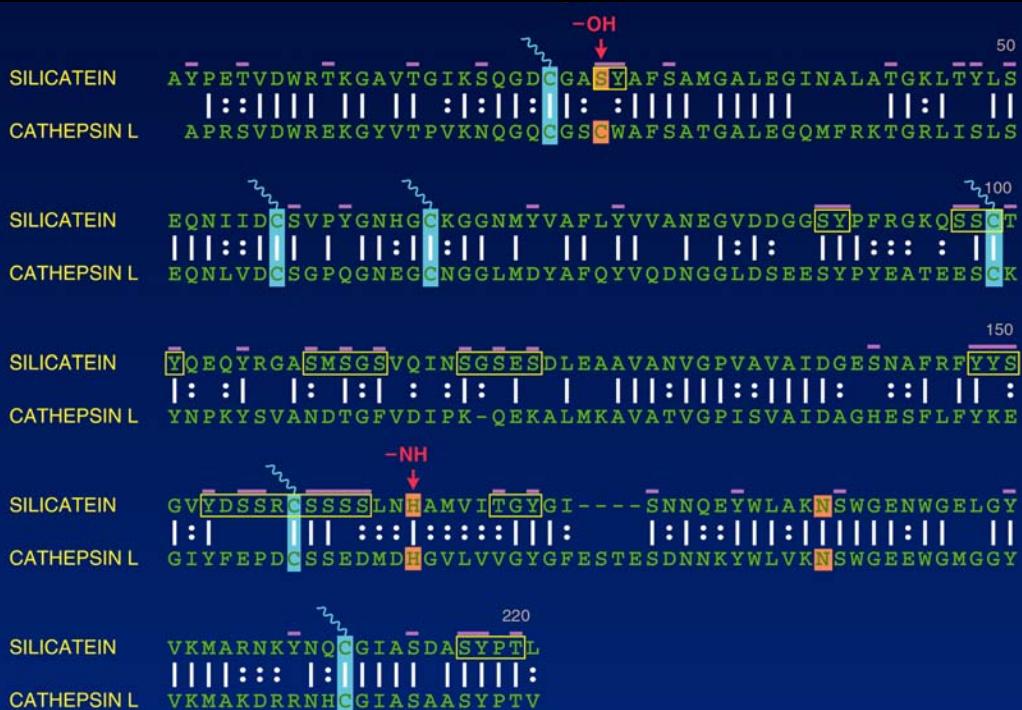
"We believe that biotechnology is one of the most

Various forms of silica and silicone: silicon metal, powders, fluids, granules, and pellets in glass beakers.

Dow Corning Corp.

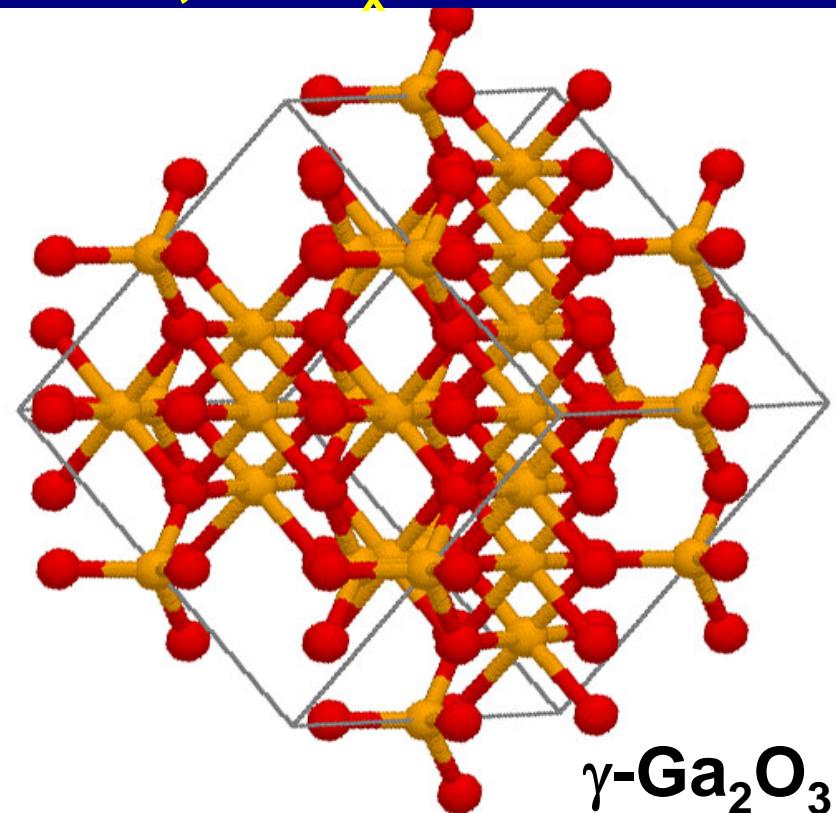


Cloning reveals:
Protein template
is an enzyme catalyst:



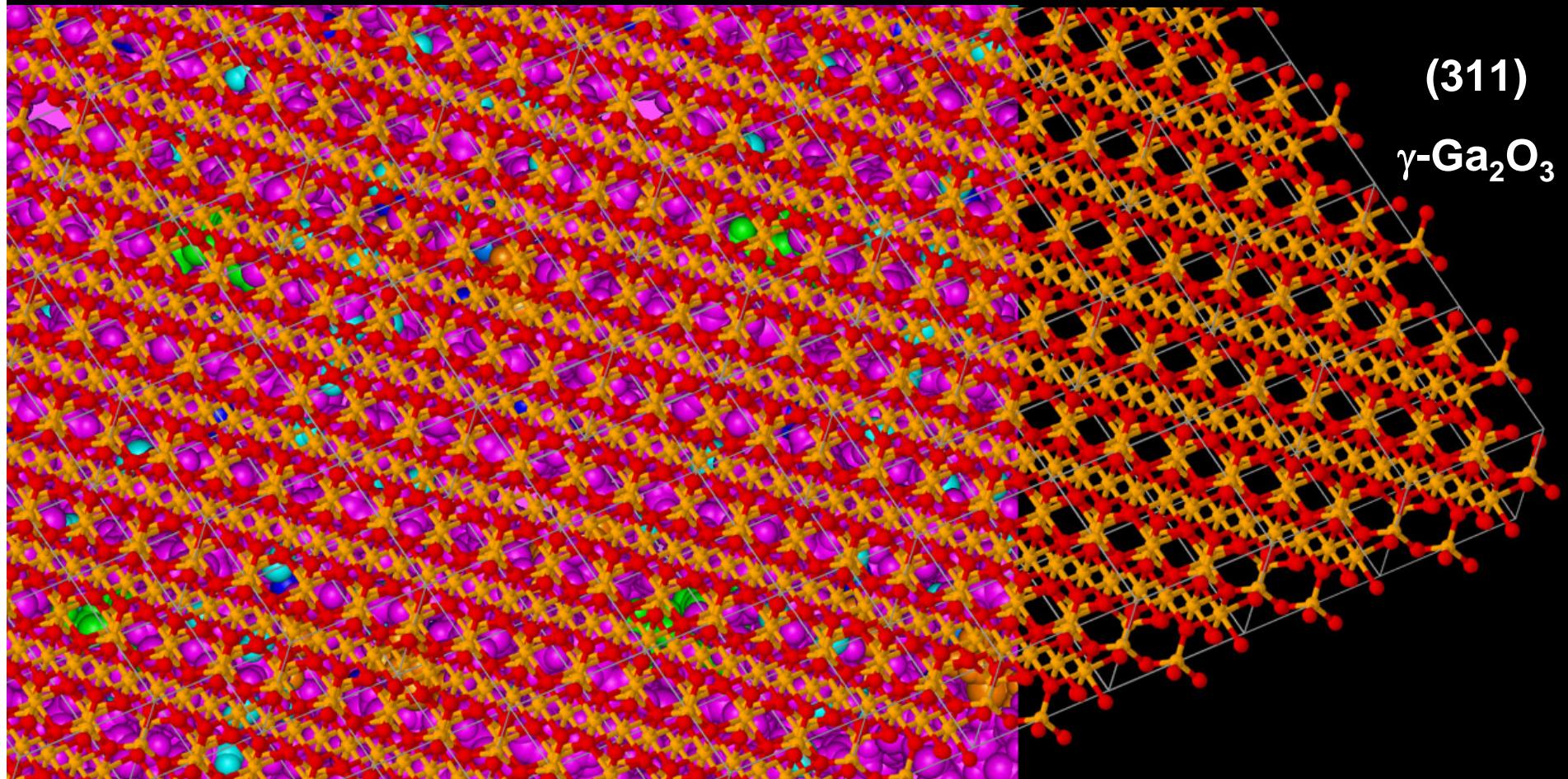
Enzyme that catalyzes & templates synthesis of silica at low temperature also makes semiconductors from molecular precursors:

TiO_2 , Ga_2O_3 , ZnO ,
 CoO , RuO_x

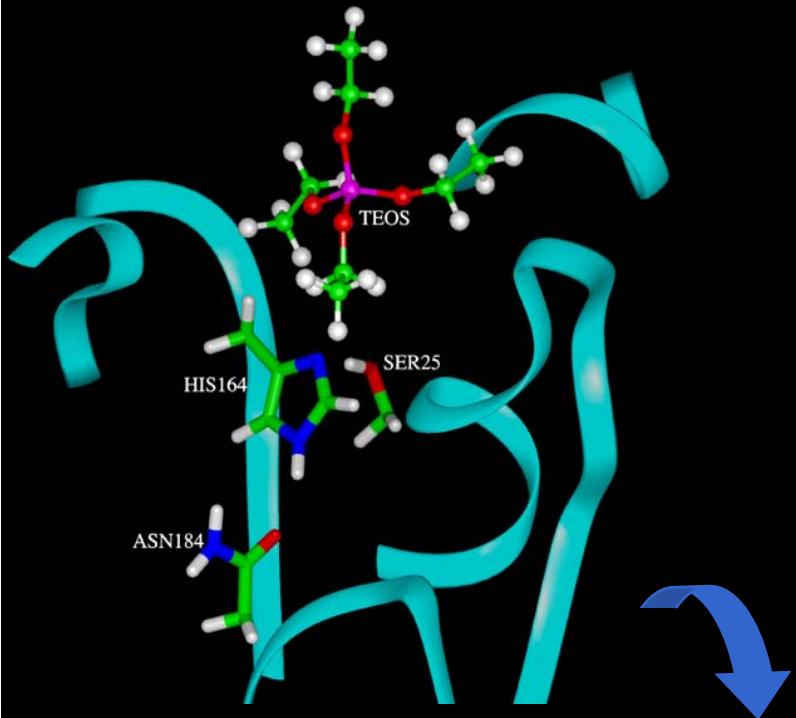


Low-temperature catalysis & templating of semiconductor synthesis

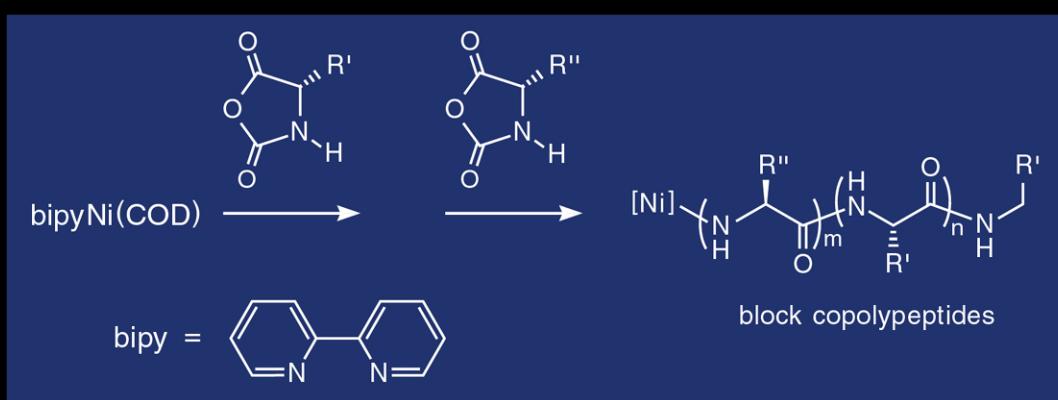
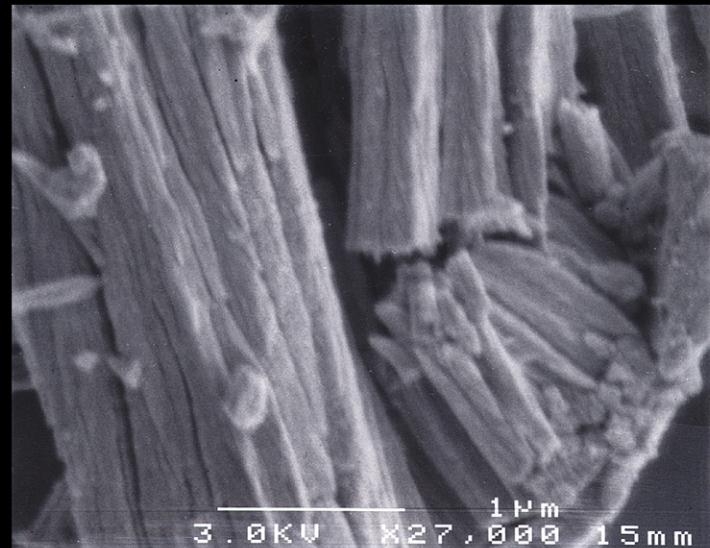
The catalyst IS the template!



Translating the Enzymatic Mechanism to “Biomimetic” Materials Synthetics



Catalytic & Structure-Directing Peptides and Polymers!



Cha, Stucky, Morse & Deming
Nature 403: 289 (2000)

Small-molecule Biomimetic SAMs on Nanoparticles

— 3 Å

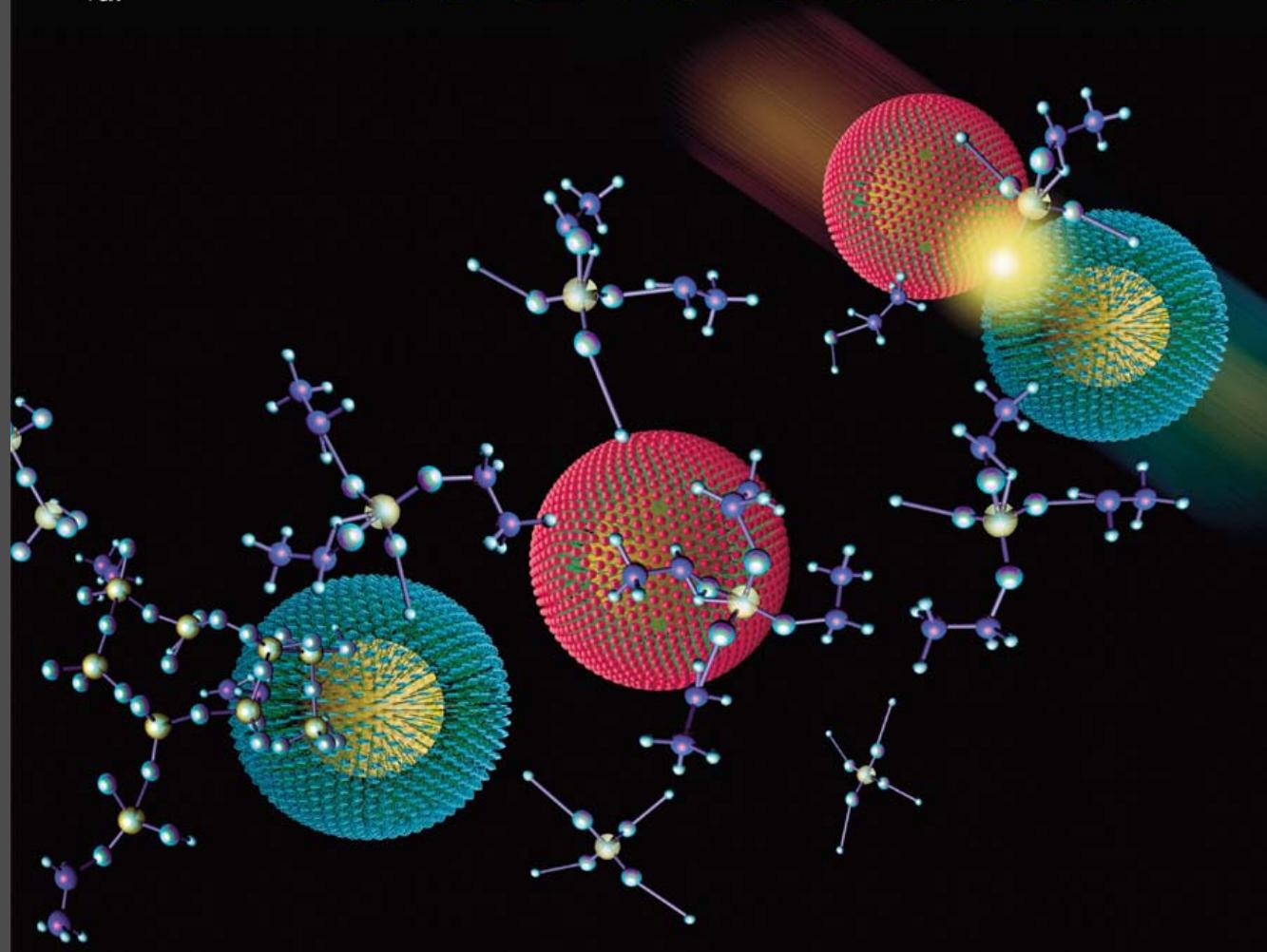
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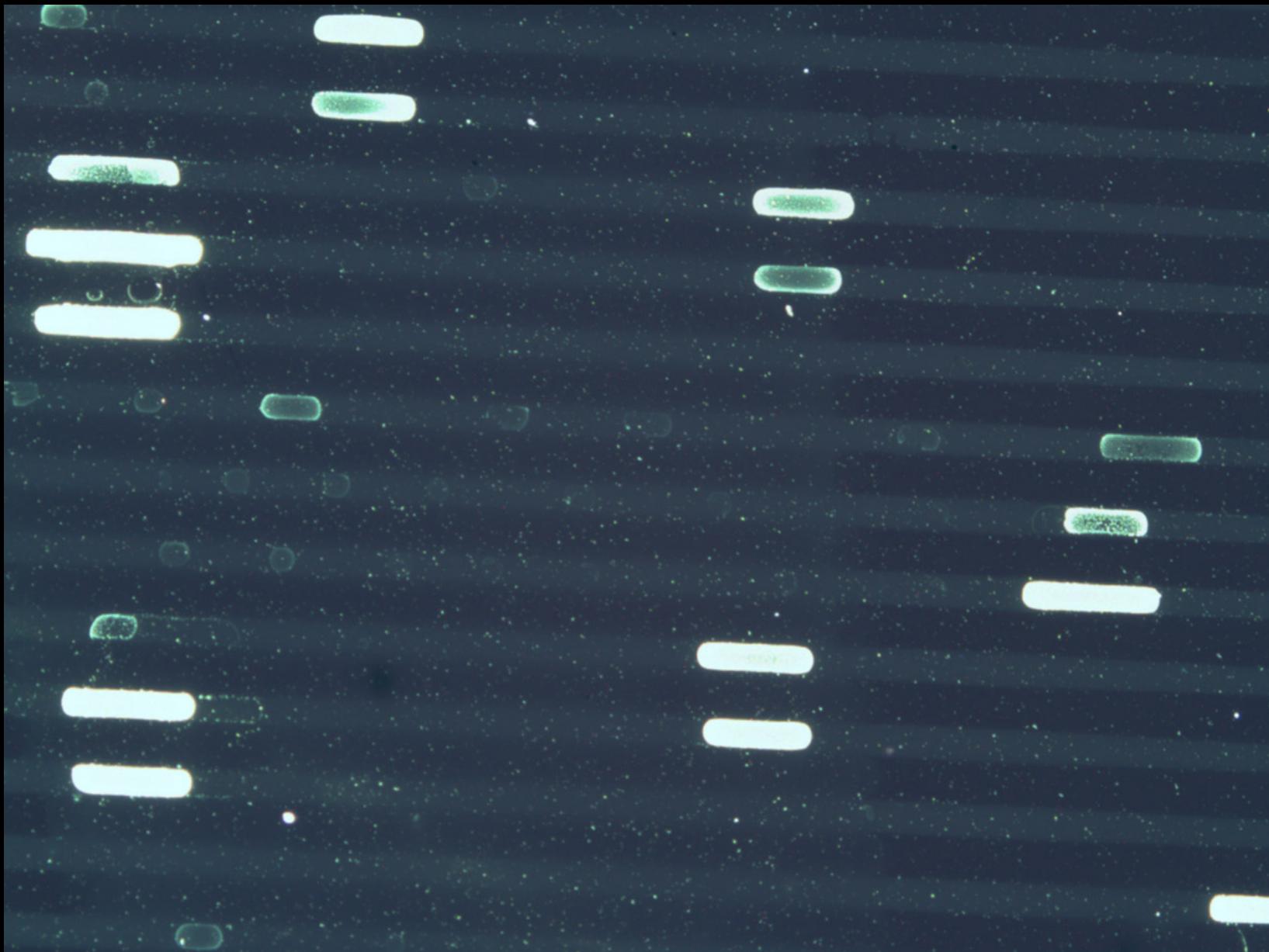


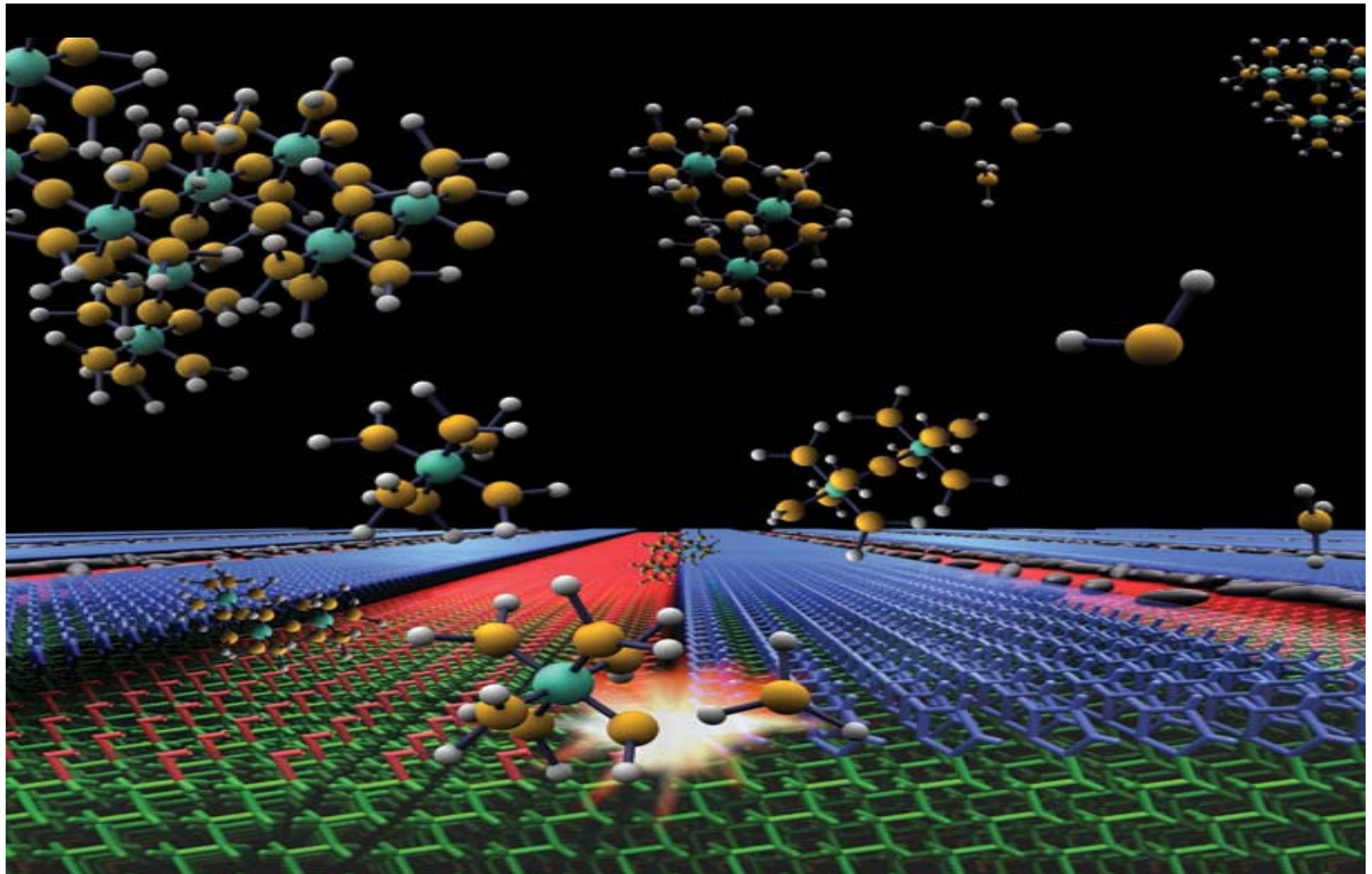
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ADVANCED MATERIALS



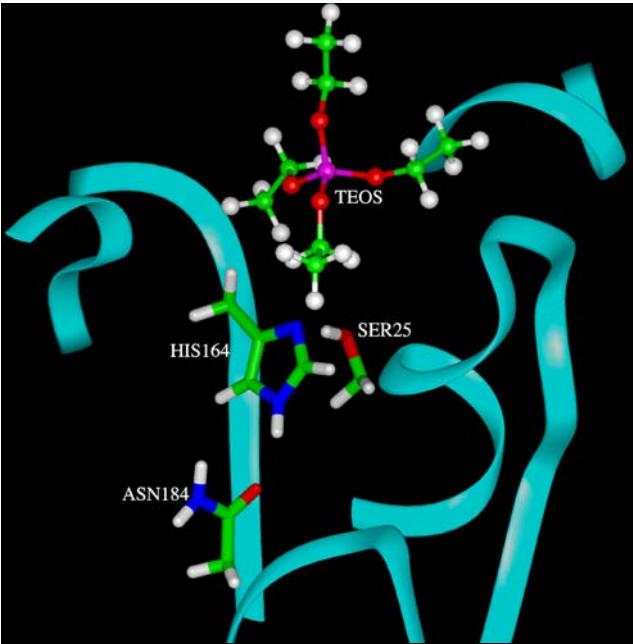
Biomimetic SAM Writes Nanoscale Pattern of Semiconductors on Silicon Chip



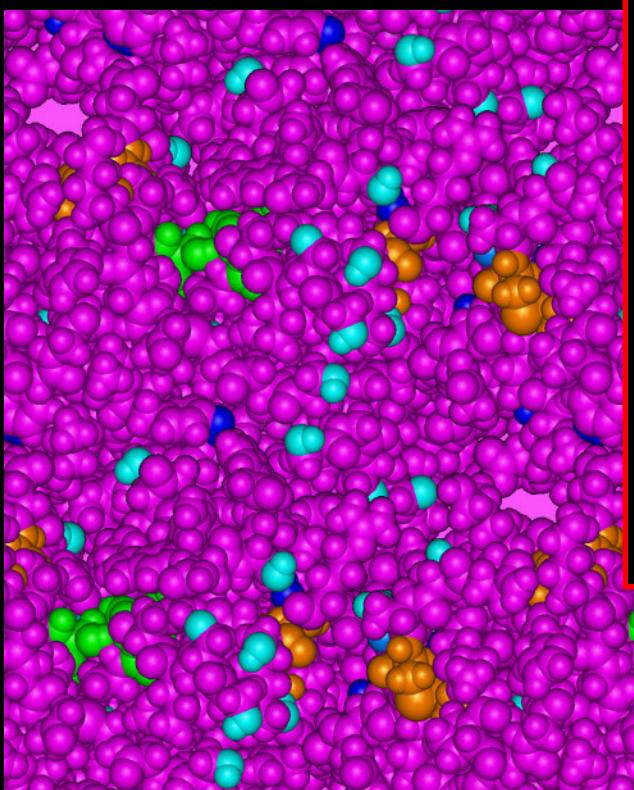
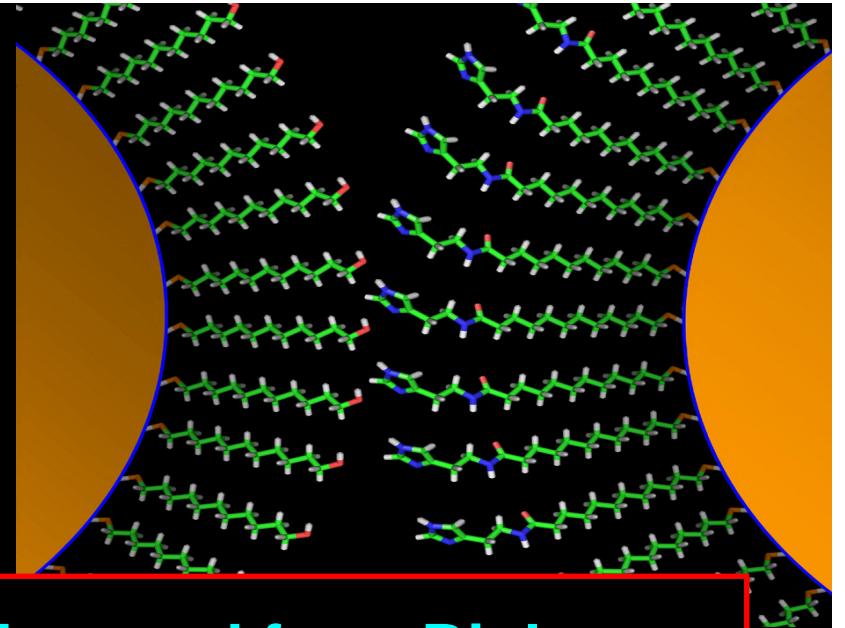


.....a low-temperature, **biocatalytic** counterpart to MOCVD!

But: can we do this with no organics?

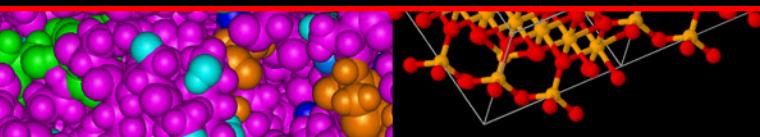


Translating
the biomolecular
mechanism.....

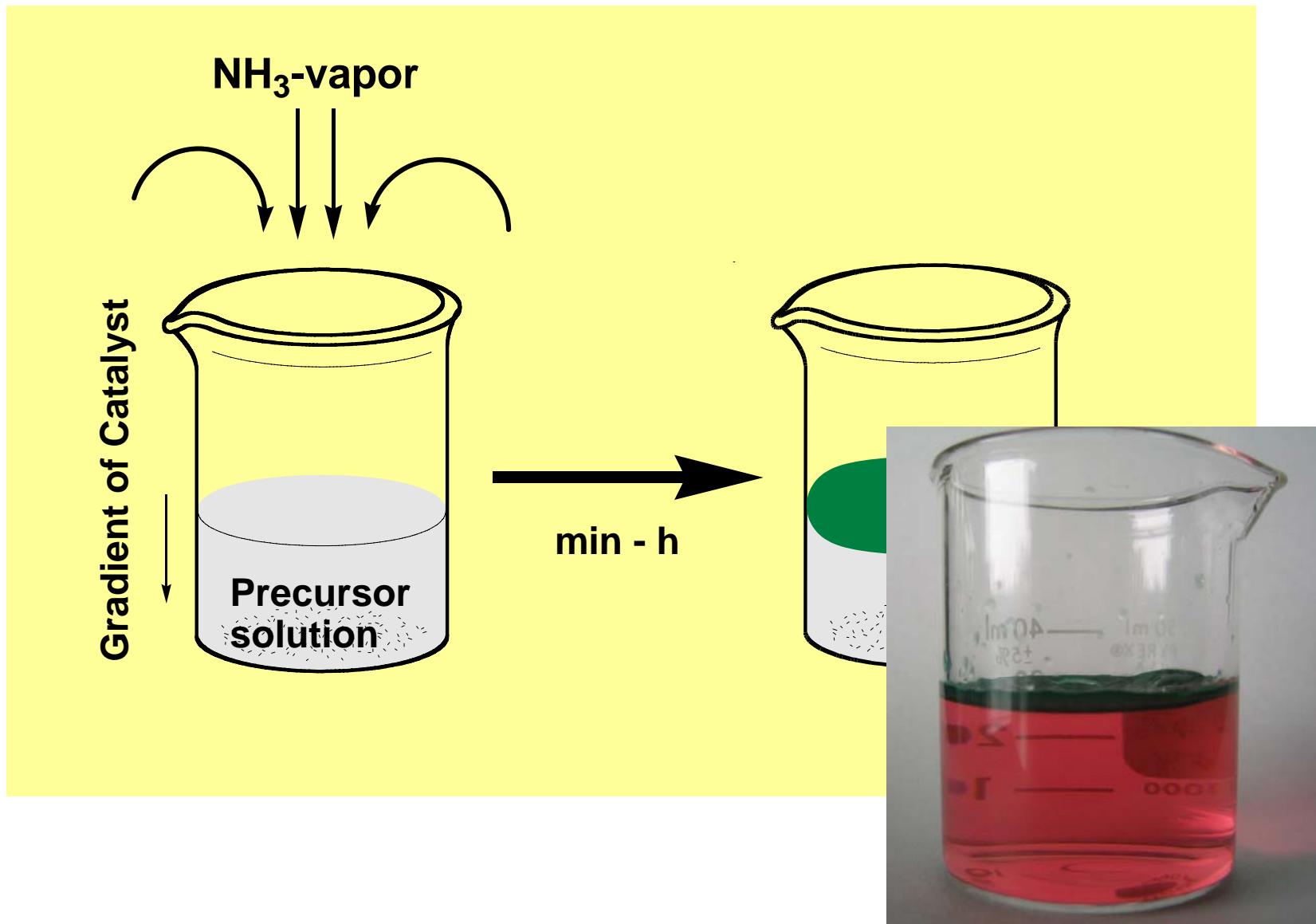


Lessons Learned from Biology:

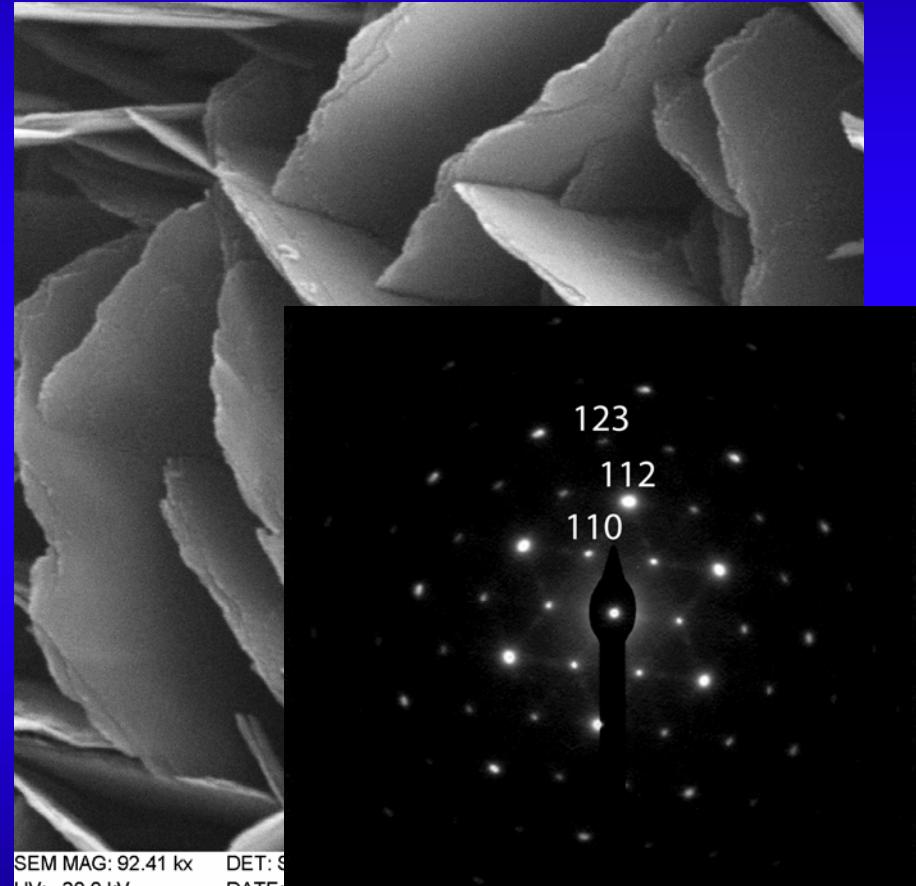
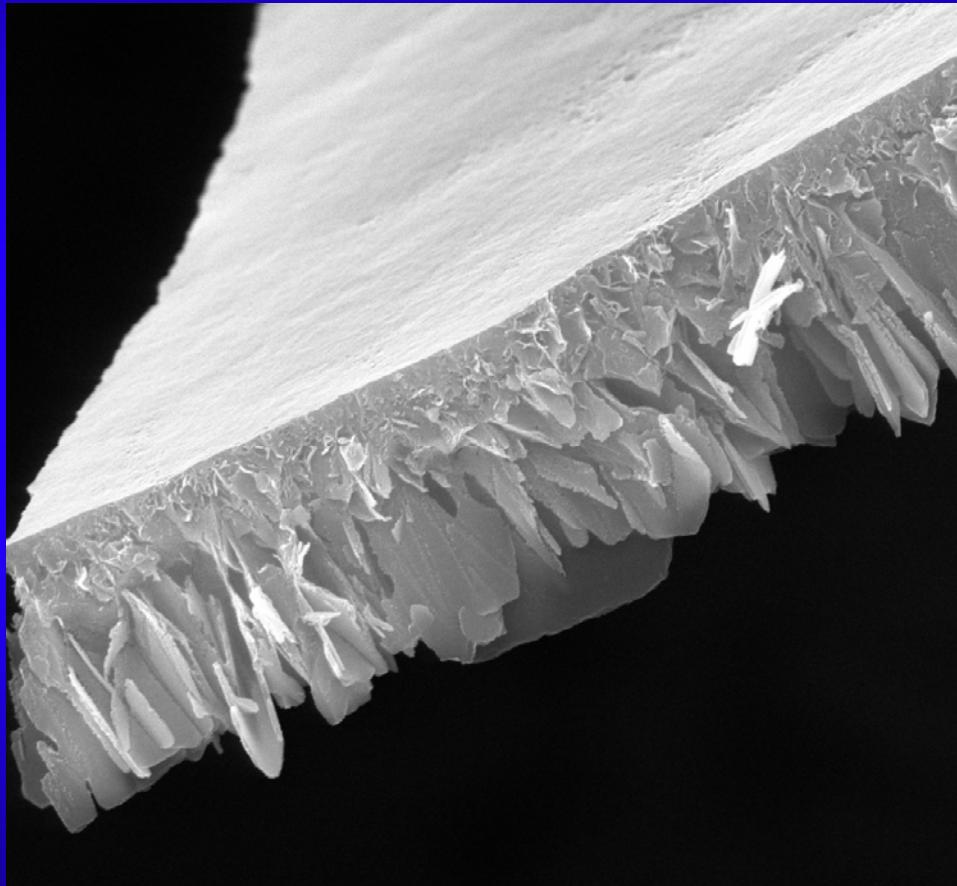
- ***Slow catalysis of synthesis from molecular precursor***
⇒ kinetic control
- ***Vectorial control of crystal growth to regulate polymorph, orientation & connectivity***



Kinetically Controlled Growth of Template -free Nanostructured Films - *with No Organics*



Bio-inspired, Low-Temperature Synthesis of Nanostructured Electronic Materials - with no biochemicals or organics!



Single-crystal Co(OH)_2 plates connected to flat conductive backplane

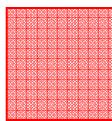
⌚ **Many Novel Materials that Can't Be Made
by Conventional Methods!**

The Method is Generic for Nanostructured Thin-Films of >30 Metal Hydroxides, Oxides, Phosphates, Nitrides and Sulfides

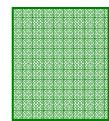
hydrogen 1 H 1.0079	lithium 3 Li 6.941	beryllium 4 Be 9.0122
sodium 11 Na 22.990	12 Mg 24.317	13 Al 26.982
potassium 19 K 39.098	20 Ca 40.078	14 Si 28.086
rubidium 37 Rb 85.468	21 Sc 47.667	15 P 30.974
cesium 55 Cs 132.91	22 Ti 47.967	16 O 15.999
francium 87 Fr [223]	23 V 50.942	17 F 18.998
radium 88 Ra [226]	24 Cr 52.000	18 Ne 20.180
	25 Mn 54.938	
	26 Fe 55.845	
	27 Co 58.933	
	28 Ni 58.693	
	29 Cu 63.547	
	30 Zn 65.391	
	31 Ga 69.721	
	32 Ge 72.61	
	33 As 74.922	
	34 Se 78.98	
	35 Br 79.904	
	36 Kr 83.80	
	37 In 114.71	
	38 Sn 115.71	
	39 Sb 121.26	
	40 Te 127.60	
	41 I 128.90	
	42 Xe 131.29	
	43 Tl 132.91	
	44 Pb 136.20	
	45 Bi 136.20	
	46 Po [209]	
	47 At [210]	
	48 Rn [222]	

boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	helium 2 He 4.0026
silicon 13 Si 28.086	phosphorus 14 P 30.974	sulfur 15 S 32.065	chlorine 16 Cl 35.453	argon 17 Ar 39.948	neon 18 Ne 20.180
germanium 31 Ge 72.61	arsenic 32 As 74.922	selenium 33 Se 78.98	bromine 34 Br 79.904	iodine 35 I 83.80	xenon 36 Xe 131.29
tin 38 In 114.71	antimony 39 Sn 121.26	tellurium 40 Sb 127.60	polonium 41 Te 128.90	astatine 42 I 131.29	radon 43 Xe 136.20
lead 44 Tl 132.91	tin 45 Pb 136.20	bismuth 46 Bi 136.20	polonium 47 Po [209]	astatine 48 At [210]	radon 49 Rn [222]

lanthanum 57 La 138.91	cerium 58 Ce 140.91	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 154.93	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.94
actinium 89 Ac [227]	thorium 90 Th [232.04]	protactinium 91 Pa [231.04]	uranium 92 U [238.03]	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [258]

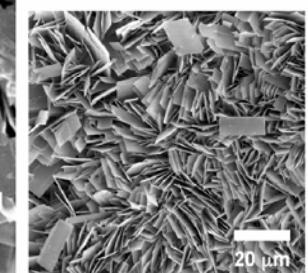
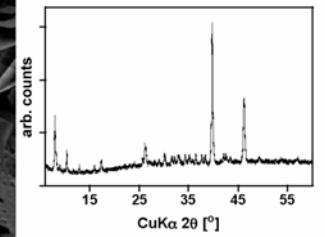
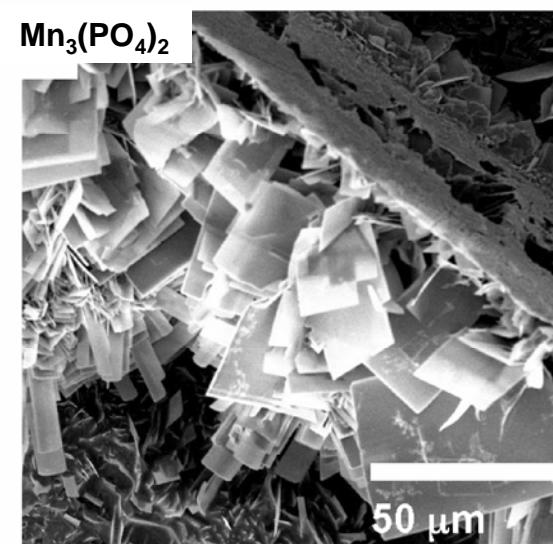
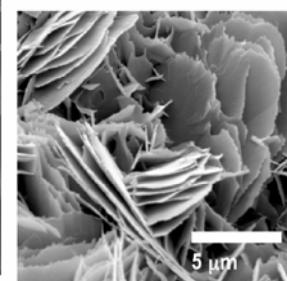
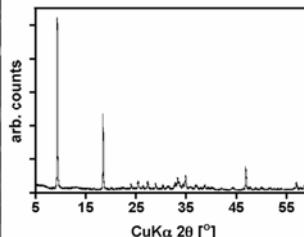
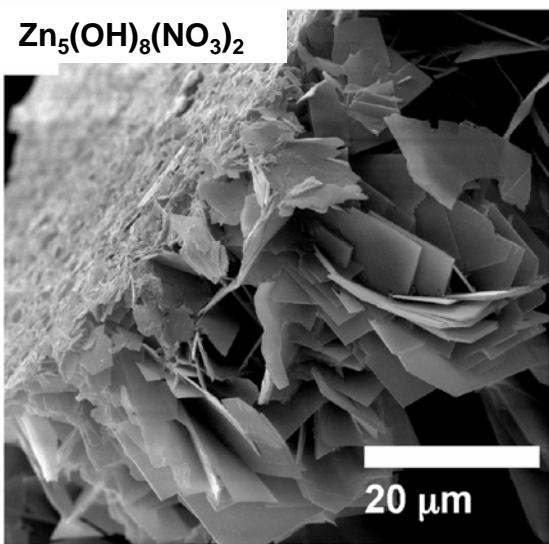
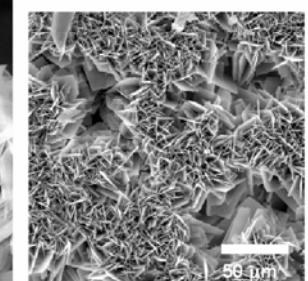
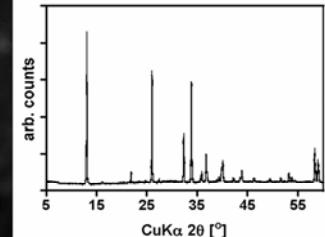
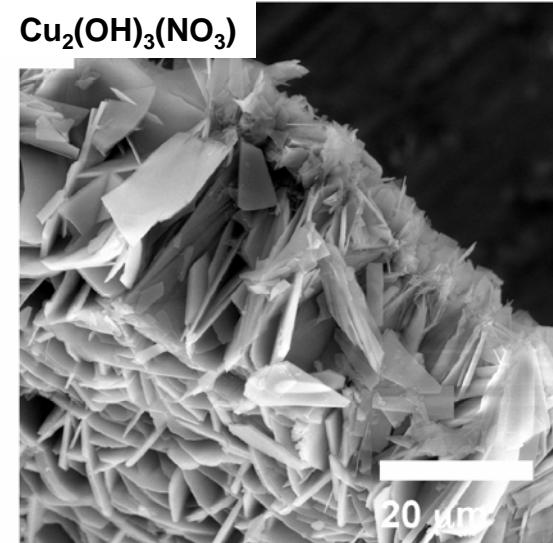
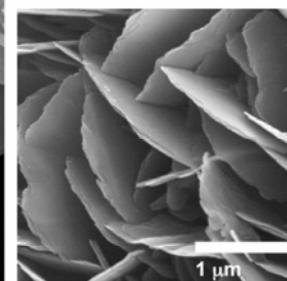
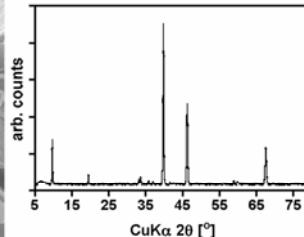
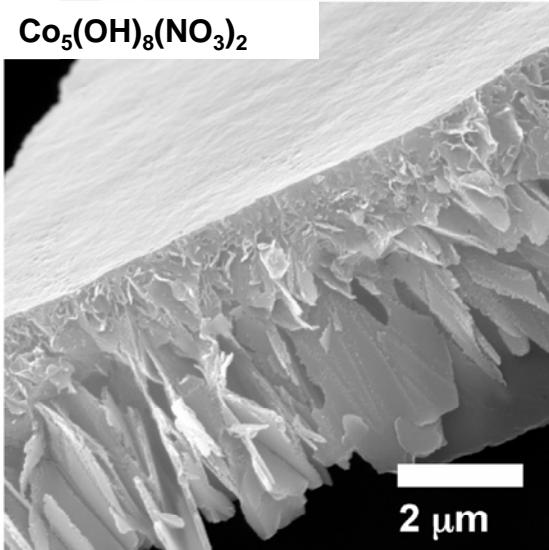


Hydroxide films

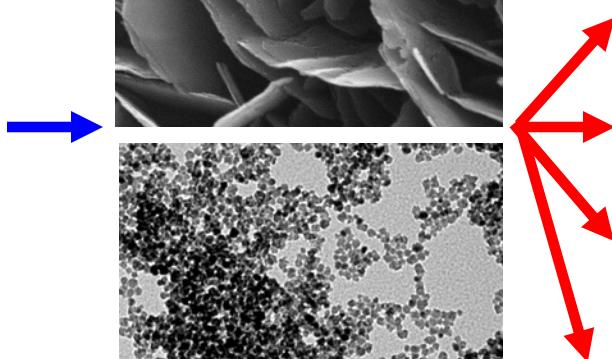


Phosphate films

Generic Synthesis of Template-free Nanostructured Films



Strong Transitioning with Army, DoD & Industry Partners



Discovered Molecular Mechanism of Biological Nanofabrication of Silica

Translated to New Bio-inspired, Low-temperature Synthesis of Nanostructured Semiconductor Thin-films and Nanoparticles

- Novel Structures;
Uniquely Useful Properties!

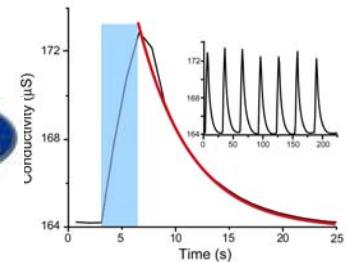
3-D Batteries

CERDEC,
Quallion



Solar Energy

DARPA



Uncooled IR

ARL,
Aerospace



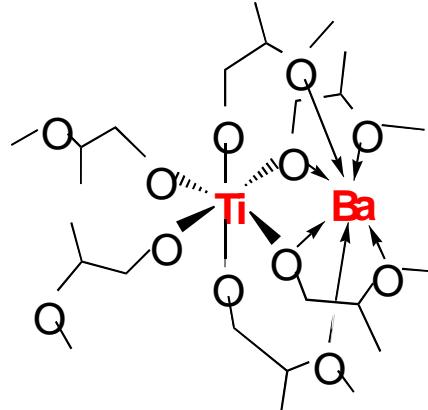
Flexible Displays

ARL,
Aerospace

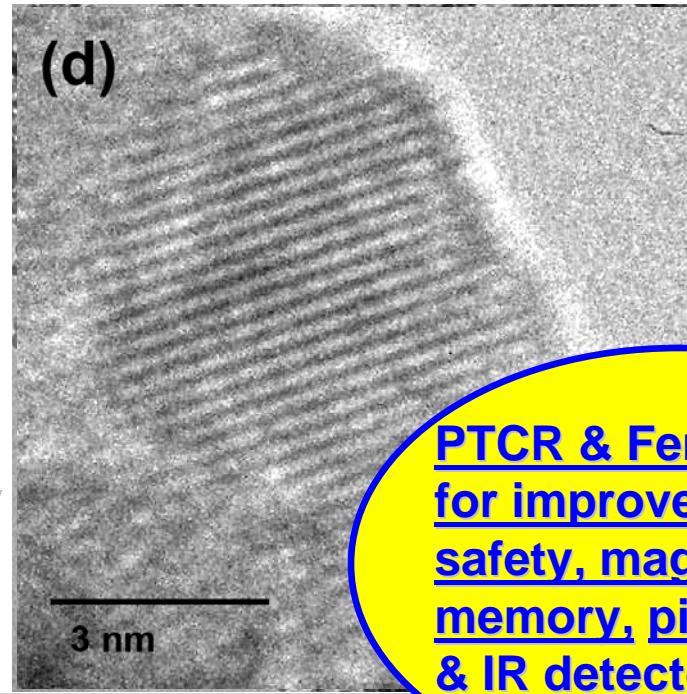
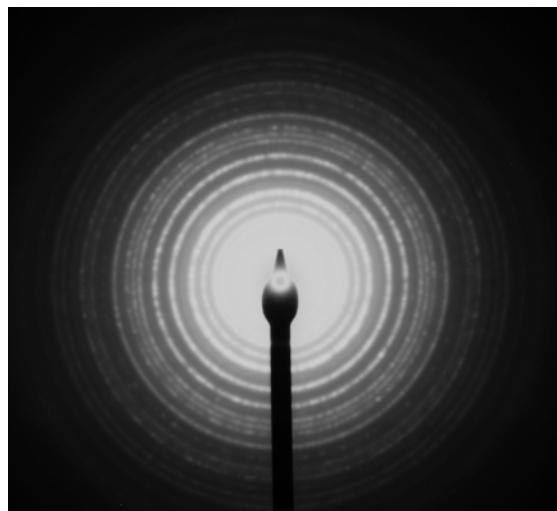


Bimetallic Perovskites:

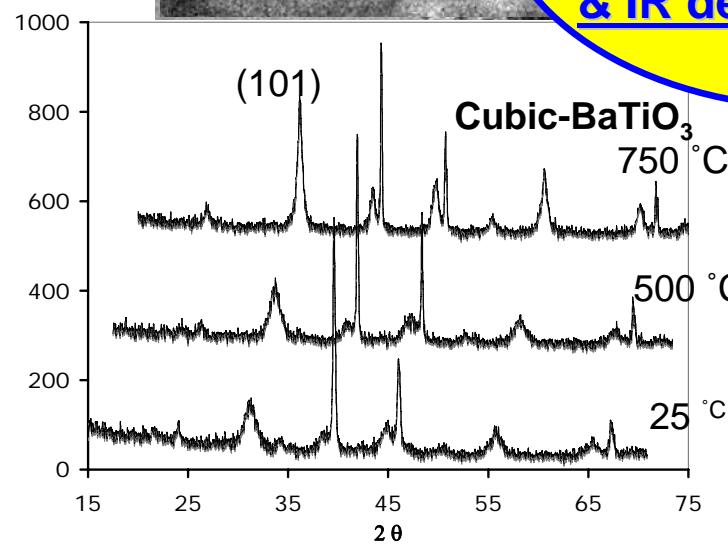
Nano-crystalline BaTiO_3 at 20 °C! – Typically requires extreme T or pH.



**Gentle, bio-inspired catalysis
preserves atomic-scale geometry
of bimetallic precursor
- with no phase-segregation!**



PTCR & Ferroelectric:
for improved battery
safety, magnetic
memory, piezoelectric
& IR detectors



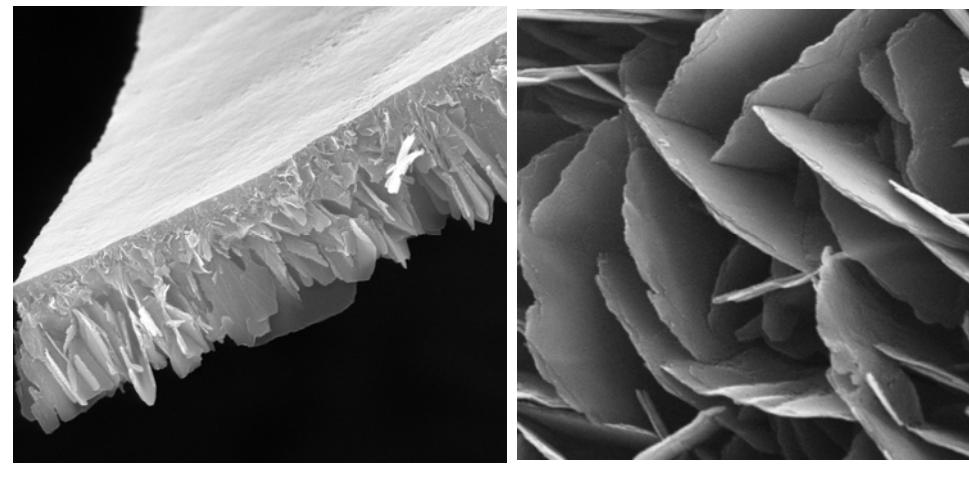
Angewandte Chemie
(in press, 2006).

Exceptional Advantages for Lightweight Portable Energy

Lightweight high power-density 3-d batteries (with CERDEC and Quallion, Inc.):

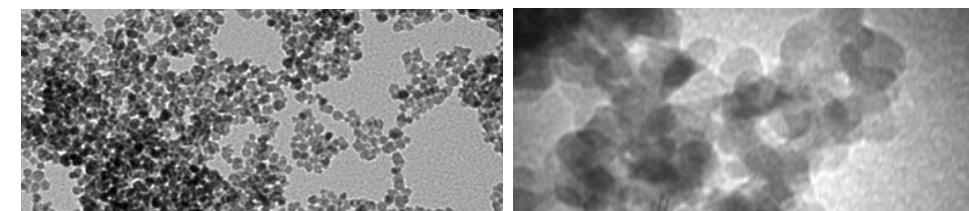
Nanostructured cobalt oxide and iron phosphate for true 3-d high power-density Li-ion batteries

(*J. Mater. Chem.* 16: 401 - 407, 2006)



BaTiO_3 nanoparticle coatings for electrodes for first explosion-proof rechargeable Li-ion batteries
(protection resulting from Positive Thermal Coefficient of Resistance)

(*Angewandte Chemie* in press, 2006)



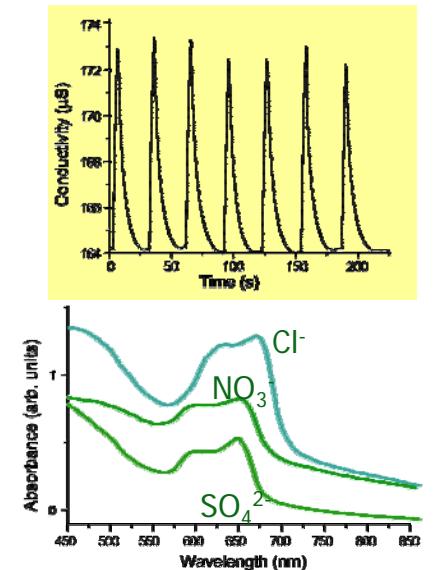
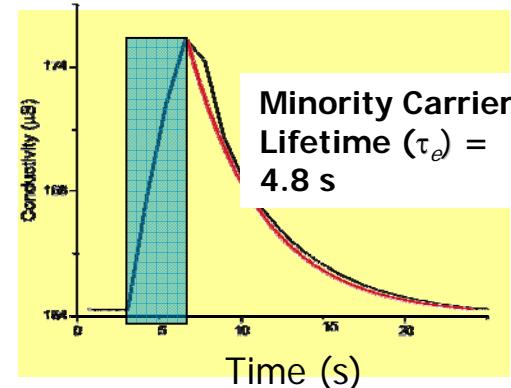
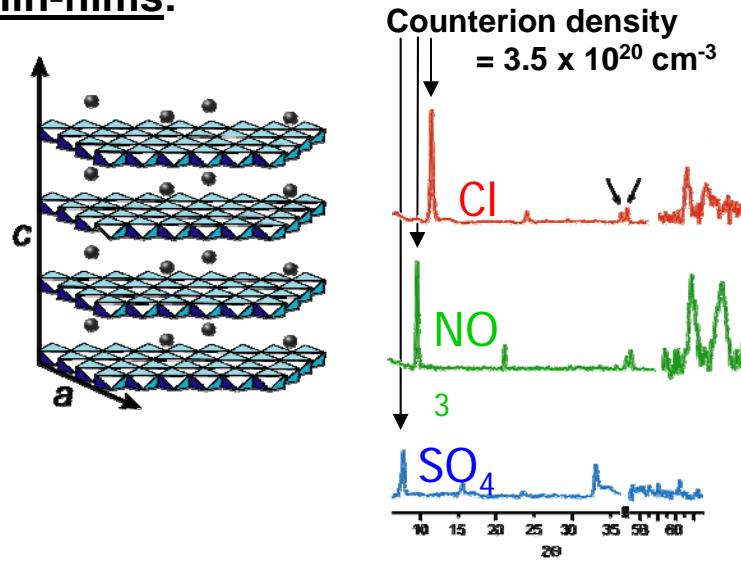
The New York Times
SONY, DELL & Apple Recall 6 Million Batteries Because of Fire Threat



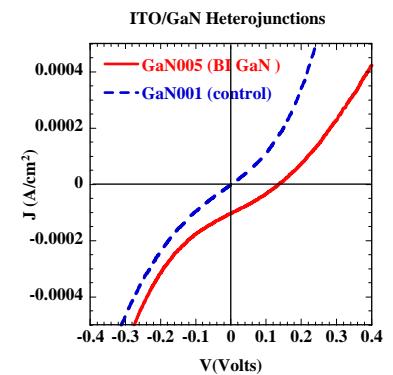
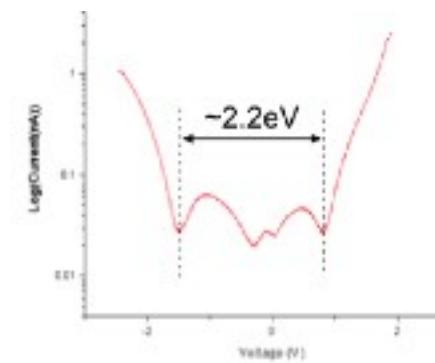
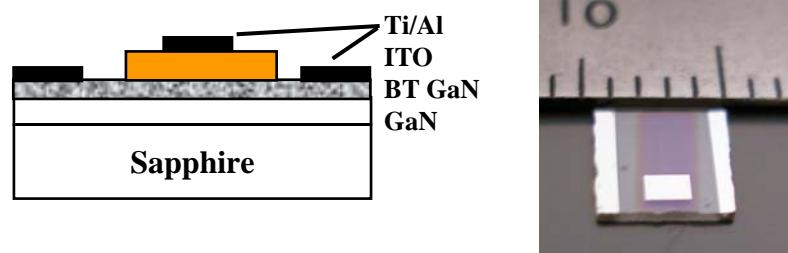
New Materials for Energy Applications:

High-efficiency photovoltaics

Novel cobalt hydroxide nanostructured thin-films:



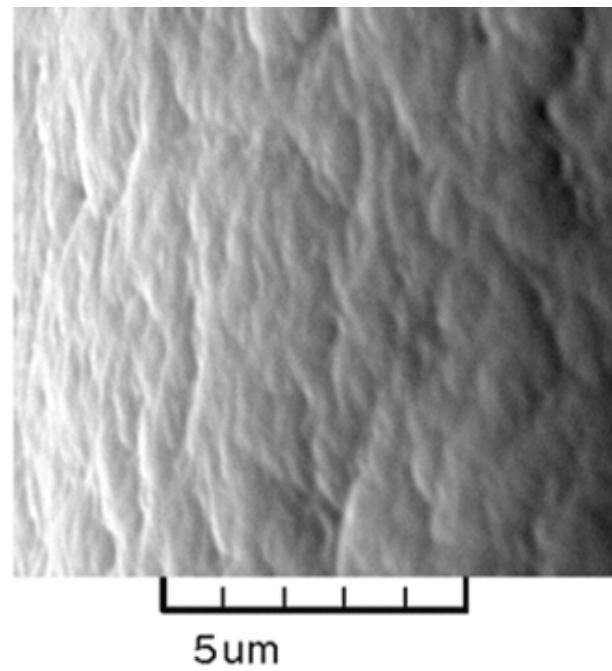
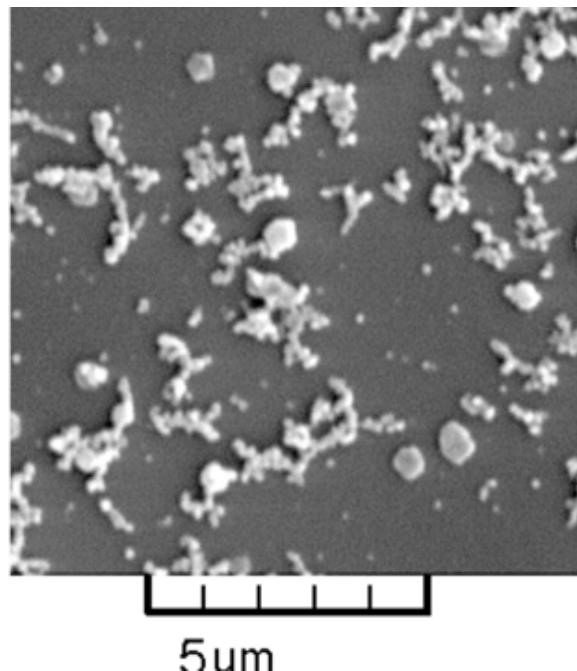
Low-cost Gallium Nitride thin-films:



New Materials for Energy Applications:

Lightweight flexible photovoltaics

Low-Temperature Growth of Thin-film Electrodes on Organic Polymer Photovoltaics: more intimate connection of TiO_2 electrode with organic polymer photovoltaic:



Discontinuous particulate TiO_2 film made by conventional sol-gel method (*l.*) and the continuous TiO_2 thin-film made by ICB's kinetically controlled (low-temp) method (*r.*)

Summary and Advantages

- Generic low-temperature method for kinetically controlled synthesis of >30 nanostructured crystalline inorganic thin films, many with morphologies not possible with conventional methods
- Conversion to Nitrides, Phosphides and Sulfides demonstrated
- Kinetic control yields good crystallinity, long minority carrier lifetimes, high dopant densities and high surface areas *advantageous for more efficient solar energy and lightweight, high power-density batteries!*
- High purity materials containing no organics
- Methods & materials fully integrable with MOCVD and CMOS fabrication
- Supported and free-standing thin films; readily amenable to electrochemical measurements ⇒ previously unknown properties
- Potentially adaptable to roll-to-roll and other high-throughput methods

Adaptive Optical Materials



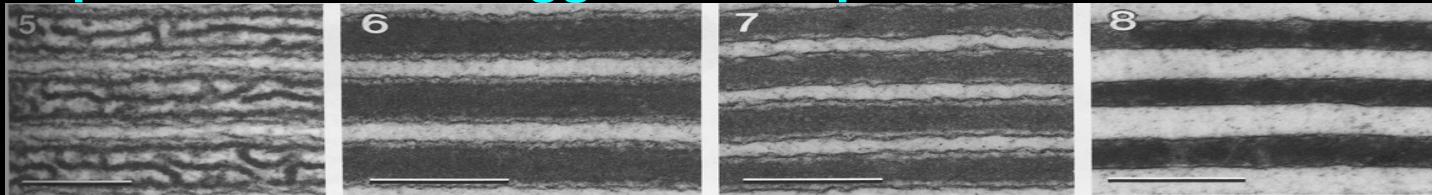
Our Approach:

**Identify the Mechanism, and Translate
to Practical Materials Synthesis and Engineering**

We recently identified the molecular switch.

- This discovery can guide new materials design!

Signal-dependent changes in the density, thickness & spacing of protein-based Bragg reflector plates determine reflectivity & color:



Non-reflecting Red

Gold/Green

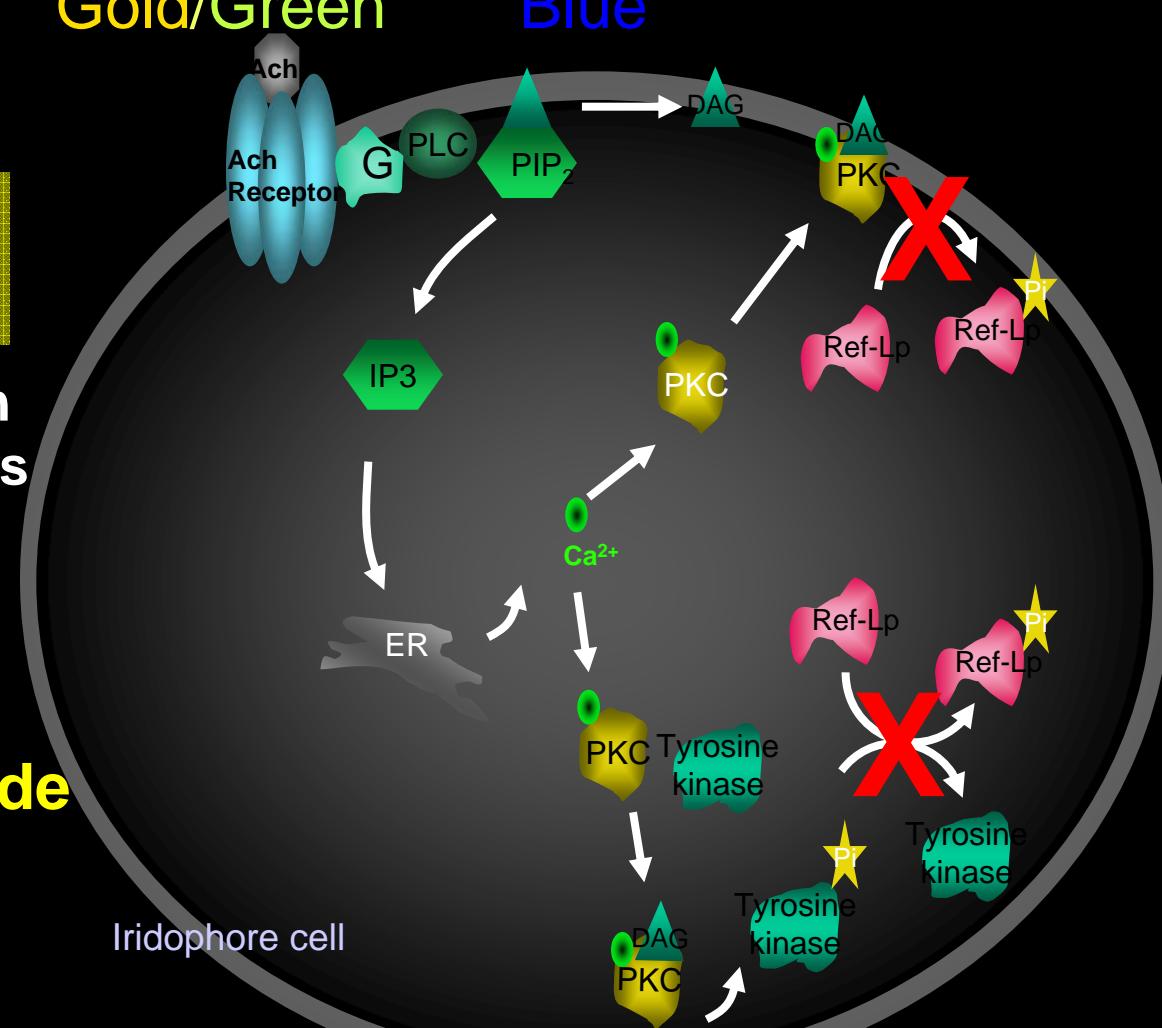
Blue

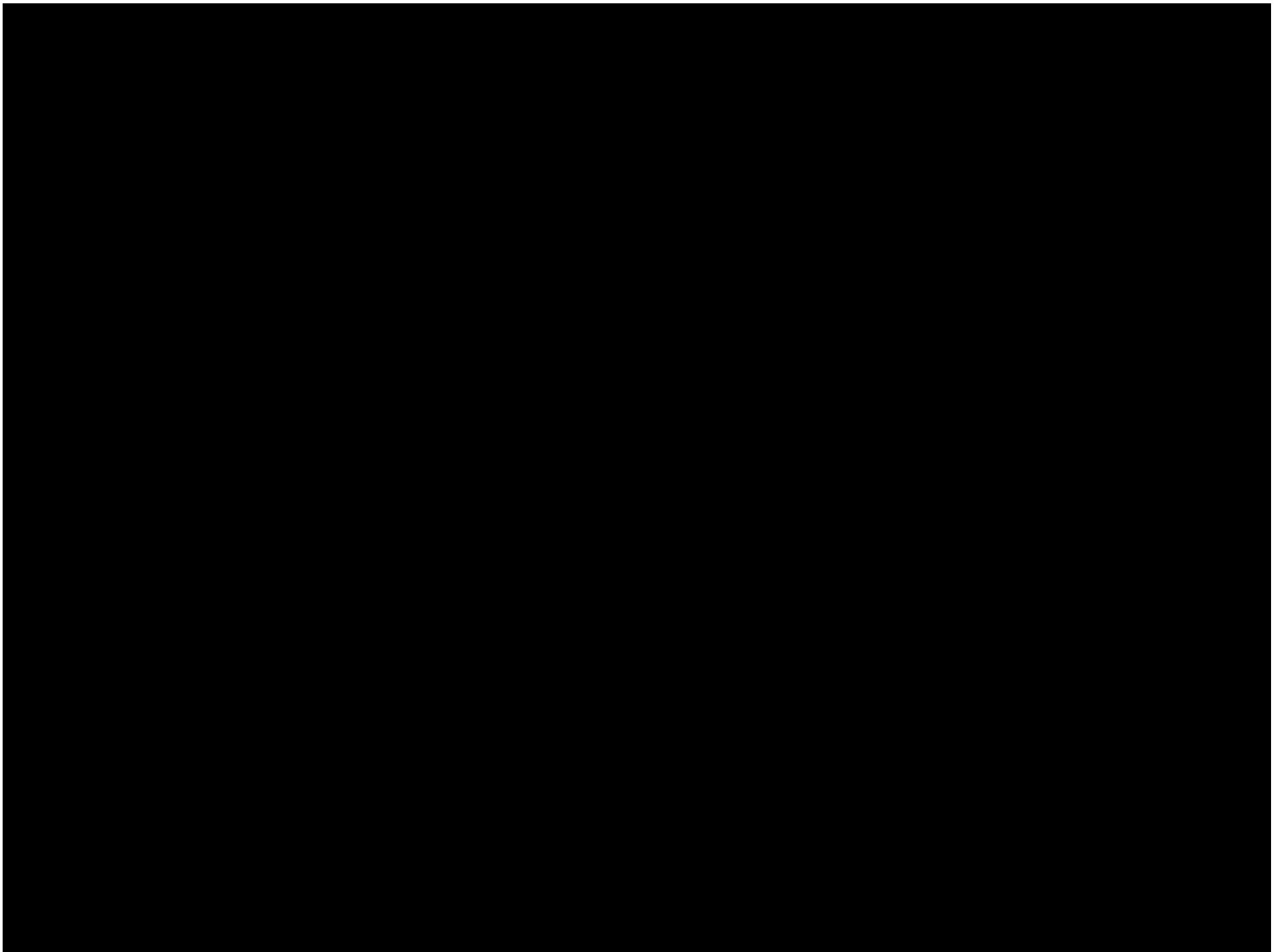
Recent discovery:
the molecular switch

Catalytic phosphorylation controls optical properties of the protein-based Bragg Reflectors.

This discovery will guide path to new materials!

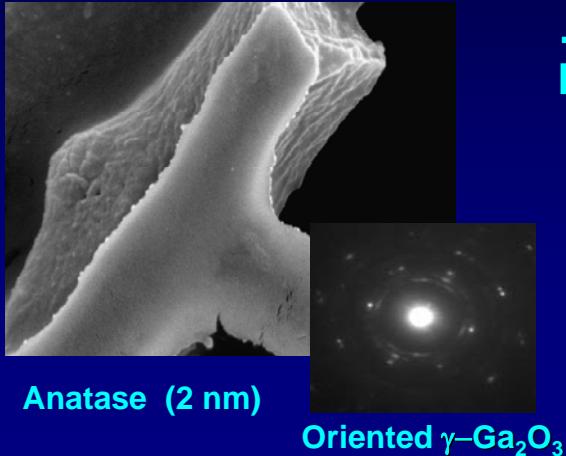
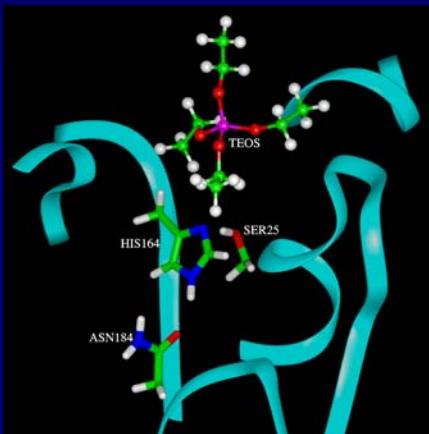
Iridophore cell



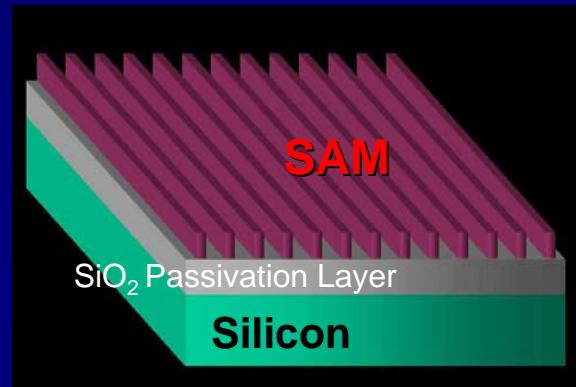


Bio-inspired, Low-Temperature Generic Synthesis of Nanostructured Semiconductor Thin-Films for Energy

Genetic engineering identified mechanism of catalysis



...that we translated to low-temperature biocatalytic counterpart to MOCVD

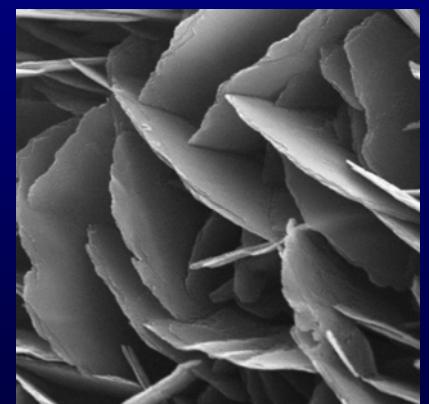
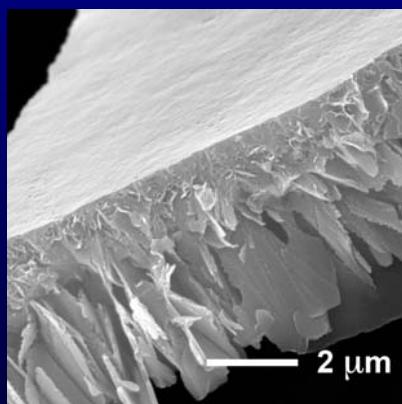


Electron diffraction and XRD revealed molecular mechanism of templating



... a paradigm shift:

Kinetically controlled vapor-diffusion synthesis of inorganic films - using no organics!



This new understanding led to...